

# On the relation between supersoft X-ray sources and VY Scl stars: The cases of V504 Cen and VY Scl\*

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We summarize our optical monitoring program of VY Scl stars with the SMARTS telescopes, and triggered X-ray as well as optical observations after/during state transitions of V504 Cen and VY Scl.

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## 1 Introduction

VY Scl stars are a subclass of cataclysmic variables (CVs) that are optically bright most of the time, but occasionally drop in brightness by several magnitudes at irregular intervals (Bond 1980, Warner 1995, Honeycutt & Kafka 2004). The transitions between the brightness levels take place within days to weeks. In their high states, these variables have the largest time-averaged mass transfer rate  $\dot{M}$  (of the order of  $10^{-8} M_{\odot}/\text{yr}$ ) among CVs, and thus are thought to be steady accretors with hot disks. The cause of the transitions is widely debated. The conventional view is that a strong reduction (or even cessation) of the mass transfer rate, either due to the magnetic spot covering temporarily the  $L_1$  region (Livio & Pringle 1994) or due to non-equilibrium effects in the irradiated atmosphere of the donor (Wu et al. 1995) causes the deep low states. A major problem of this scenario is the lack of dwarf nova (DN) outbursts during the low states (Leach et al. 1999): the disk remains subject to the thermal/viscous instability as it must drain its remaining gas onto the white dwarf (WD) through a series of DN eruptions. Another serious difficulty is that the observed dual-slope rises (Honeycutt & Kafka 2004), which are faster when the system is fainter, are opposite to the expected behaviour of an accretion disk since rebuilding the disk from an extended low state should initially take place on the slow viscous timescale of the low-state disk, eventually switching to a faster rise as the disk goes into DN outburst on the faster thermal timescale.

Two unconventional views invoke quasi-stable burning of the accreted hydrogen on the white dwarf surface or a magnetic nature of the white dwarf. In the former case, VY Scl stars may be transient supersoft X-ray sources during optical low-states (Greiner & DiStefano 1999, Greiner 2000, Honeycutt 2001). Discovering more nearby supersoft X-ray sources is potentially important, since some of them may be progenitors of Type Ia supernovae; in addition, the sources may play an important role as ionizers of the interstellar medium. This picture is motivated by the behaviour of the classical supersoft X-ray source RX J0513.9–6951 which has quasi-periodic optical intensity dips of  $\sim 4$  weeks duration (Southwell et al. 1996, Reinsch et al. 2000) simultaneously to X-ray high states. This is interpreted as being due to a drop in accretion rate which leads to a contraction of the WD, and in turn a hotter WD surface temperature. Besides this phenomenological similarity, there exist independent observational hints for transient supersoft X-ray emission in 5 VY Scl stars: V751 Cyg (Greiner et al. 1999), V Sge (Greiner & Teeseling 1998), DW UMa (Knigge et al. 2000), SW Sex (Groot et al. 2001), BZ Cam (Greiner et al. 2001).

This conjecture that VY Scl stars are the low-mass extension of supersoft X-ray binaries (SSB) can only be tested by combined optical and X-ray observations. If it can be proven, it is expected to have far-reaching consequences. For example, if a relation to SSBs can be established, it would add a whole group of optically bright objects that are much easier to study than the optically-faint SSBs. Second, because the presence of WDs in SSBs has never been proven, a connection of SSBs and VY Scl stars would add support to the standard model of supersoft X-ray sources (van den Heuvel et al. 1992). Third, the irradiation of the

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donors in supersoft X-ray sources is much stronger than in CVs (and VY Scl stars), and therefore the mechanism proposed by Wu et al. (1995) for VY Scl stars could be readily applicable to SSBs.

In the case of a magnetic primary, a low magnetic field of order  $5 \times 10^{30}$  G cm $^3$  would disrupt the inner, otherwise unstable accretion disk, and thus prevent outbursts in low states, suggesting that VY Scl stars may all be intermediate polars (Hameury & Lasota 2002). While variable circular polarization (and consequently a magnetic field) has been found in two VY Scl stars (LS Peg and V795 Her), the majority has no measurable magnetic field. This conjecture can be "easily" tested by X-ray observations (searching for X-ray pulsations) or optical spectropolarimetry.

Here, 10 yrs after the first suggestion (Greiner & Di Stefano 1999), we report on our results of long-term optical monitoring of southern VY Scl stars, and triggered follow-up optical and X-ray observations when a VY Scl star went into an optical low-state.

## 2 The monitoring program

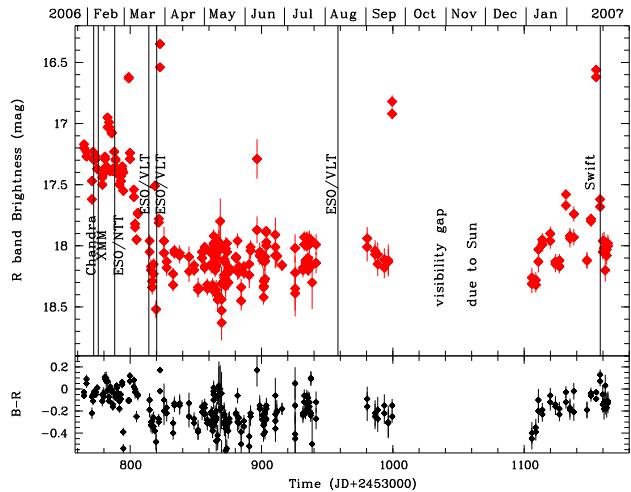
We primarily selected VY Scl stars with known distance, so that we could determine the X-ray and optical luminosity: PX And, TT Ari, KR Aur, MT Pup, SW Sex, ST Cha, V504 Cen, LX Ser, V442 Oph, V794 Aql, LQ Peg, VY Scl and VZ Scl. Monitoring observations were performed 2004–2009 with ANDICAM on the SMARTS 1.3 m telescope in *B*, *R* and *J* once every  $\approx 4$  nights throughout their visibility periods. For the occurrence of optical state transitions, we were prepared by either pre-approved or ready-to-submit target-of-opportunity proposals to obtain X-ray observations, optical spectroscopy as well as optical spectro-polarimetry.

Two objects of our sample exhibited an optical state transition, and these are described below in more detail.

### 2.1 V504 Cen

V504 Cen (also AN 354.1935) is a poorly studied CV, and was proposed as a member of the VY Scl class by Kilkenny & Lloyd Evans (1989). The first-ever well-covered fading episode was reported by Kato & Stubbings (2003) based on data of the all-sky survey ASAS-3 of 2002. The duration of the fading episode was about 200 days, with an amplitude of  $> 2$  mag (only upper limits were obtained). No distance or orbital period has been reported for V504 Cen.

V504 Cen has been monitored at the 1.3m SMARTS telescope in CTIO/Chile since 2004. Folding the long-term monitoring data from the low-state (excluding the Jan-Mar data because of the higher intensity level), we obtain an orbital period of 4.21 hrs (Fig. 2), with the following ephemeris:  $T_{\text{min}} = 0.17556655 \times E + 2453909.61279$ . This period is confirmed (Fig. 2) with 2–3 hrs phase-resolved I-band imaging in each of 5 nights, spread through 2006 and 2007.

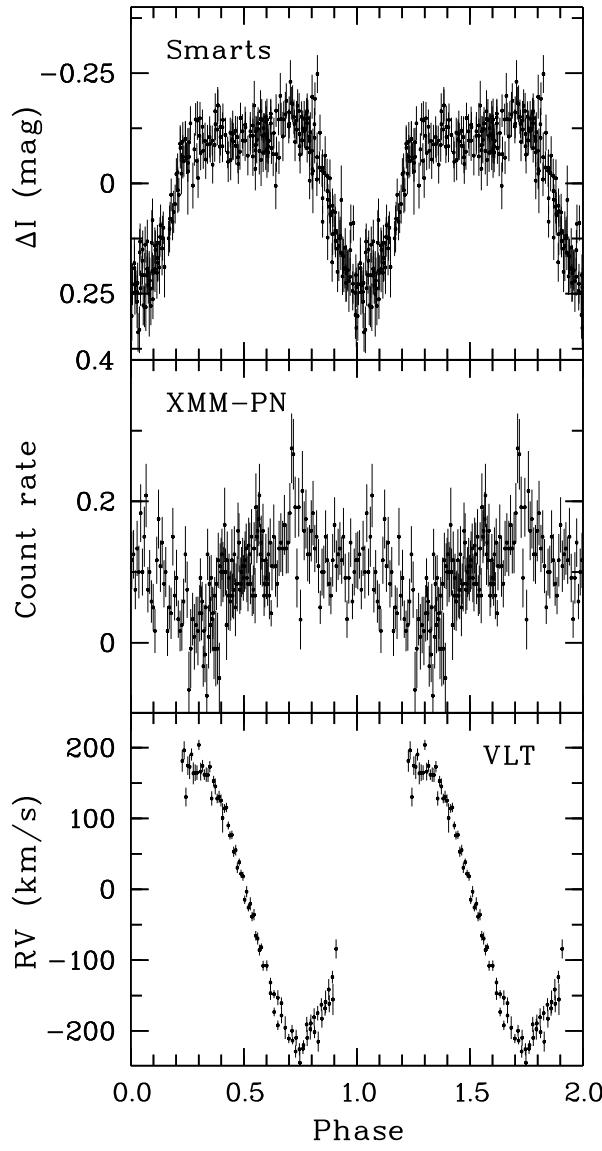


**Fig. 1** Light curve of V504 Cen in the R band (top) and its  $B - R$  color (bottom) as obtained with our SMARTS program since January 2006. The typical high-state brightness is 12.2 mag. The scatter in the low-state is most likely completely due to the orbital variability (see Fig. 2). Overplotted are the times at which Directors Discretionary Time (DDT) or Target-of-Opportunity (ToO) observations at other facilities were triggered. Note the color change when going from the intermediate state of 17.3 to the low-state at 18.3 mag in Mar. 2006. The Swift ToO was attempted quickly after the recognition of the brightening, which turned out to be a flare and not the rise back to the bright state. V504 Cen remained in its low-state since then, and still is as of April 2009, the end of our monitoring campaign. This is particularly long for VY Scl stars.

When VSNET on 26 Jan. 2006 reported a drop in brightness, our monitoring had just resumed after the visibility-break due to the nearby Sun, and observations (in 3 colors) confirmed the fading: the source had gone from  $B = 12$  mag (last observation 19. Sep. 2005) down to  $B \sim 17.0$  mag, and later went even further to  $B \sim 18.0$  mag in March 2006. We subsequently triggered observations with Chandra, XMM-Newton, VLT (ESO), and Swift (Fig. 1).

The Chandra observation on Feb. 6, 2006 clearly detected V504 Cen at  $0.068 \pm 0.005$  cts/s, however not with a soft X-ray spectrum. Photons up to 2 keV are detected, and the data are best fit with a power law model with photon index  $3.2 \pm 0.5$ , and foreground absorption consistent with zero ( $\chi_{\text{red}} = 1.1$ ). Bremsstrahlung ( $kT = 0.4$  keV) or black-body ( $kT = 0.14$  keV) models fit substantially worse. We did not detect a soft X-ray spectrum 11 days after the first report of optical faintness; this time span is a lower limit since the beginning of the optical low-state is unobserved.

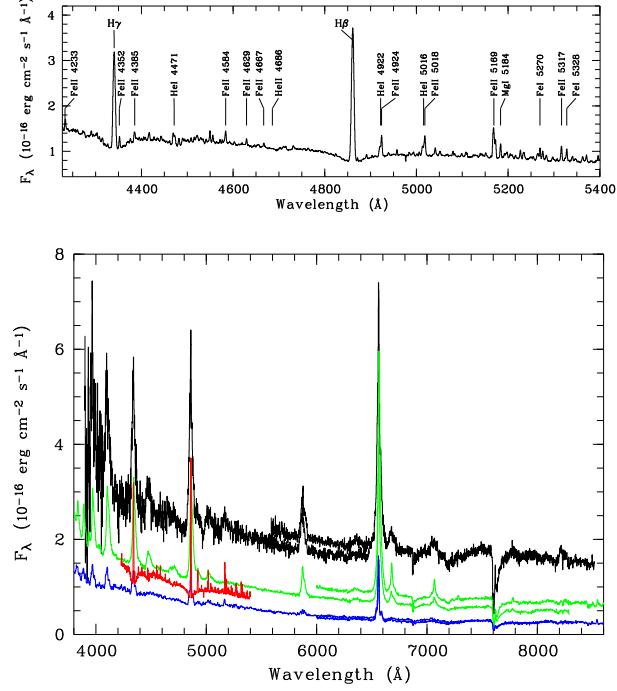
The XMM-Newton observation was performed on Feb. 9, 2006 for 20 ksec. Photons are detected up to 9 keV, and the spectrum is best fit with a two-temperature MEKAL model, with 0.83 keV and 5.64 keV. Also the 6.7 keV iron line is clearly detected. The best-fit absorbing column is  $N_H = 6.5 \times 10^{20}$  cm $^{-2}$ , corresponding to the foreground galactic value (Dickey & Lockman 1990). The unabsorbed 0.2–10.0 keV flux is  $4.3 \times 10^{-13}$  erg cm $^{-2}$  s $^{-1}$ , corresponding to  $1.2 \times 10^{31}$  (D/500 pc) $^2$  erg/s. No X-ray pulsations with pe-



**Fig. 2** **Top:** All SMARTS I-band photometric data of V504 Cen folded over our best fit period of  $252.816 \pm 0.020$  min  $\equiv 4.21$  hrs. **Center:** XMM-pn light curve folded over the same period. Note the distinct shift of the X-ray versus the optical minimum. **Bottom:** Radial velocity curve of the iron lines (Fig. 3). The optical minimum coincides with the blue-red zero-crossing. However, the width of nearly 0.4 phase units is too large for the occultation of an accretion disk by the companion.

riod longer than 4 min and with amplitude larger than  $\sim 5\%$  were detected.

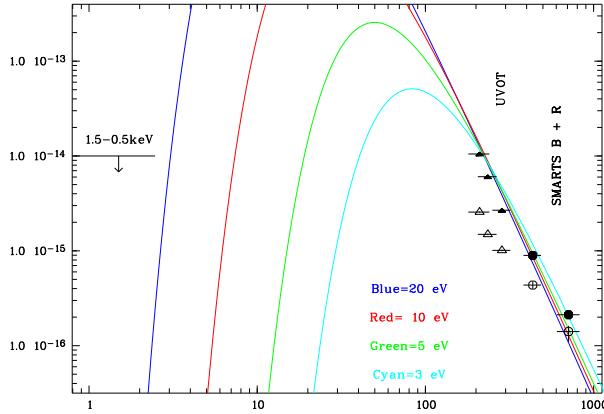
Spectra were obtained with the ESO NTT on Feb 10, 2006 with grating #8 to cover the red part of the spectrum. The mass donating star is clearly identified; the spectral type is M3 $\pm$ 1. The donor contributes about 20% of the light in the red during this time ( $m_R \sim 19$  mag). With the absolute flux calibration and using the semi-empirical absolute magnitude of CV secondaries (Knigge 2006), in our case  $M_R = 9.57$  mag, this places V504 Cen at a distance of 600 pc.



**Fig. 3** Spectra of V504 Cen (bottom panel) obtained with EMMI/NTT on Feb. 10, 2006 (black) and FORS1/VLT with different grisms on March 10 and 21-24, 2006. The mean spectrum (top panel) shows a wealth of low-ionization Fe lines, most likely from the heated side of the donor. No HeII 4686 Å is detected.

The ESO/VLT observations were performed at two occasions: Firstly, 5 hrs phase-resolved FORS1 spectroscopy was done March 20–24, 2006. Secondly, FORS1 was used in spectro-polarimetry mode on Aug. 11, 2006. The March observations reveal a wealth of FeII lines, strong Balmer lines in emission, but no HeII (Fig. 3). Both the iron as well as the Balmer lines were used to obtain a spectroscopic period of 4.21 hrs (coincident with the photometric period). The spectro-polarimetry with FORS1/600B was compromised by mediocre conditions. We did not detect circular polarization in the mean spectrum at a level higher than 3% ( $3\sigma$  level). This level of polarization is substantially above the range of polarization we were aiming for to detect, namely 0.1%. Unfortunately, therefore, the result is inconclusive, since the other two VY Scl stars with reported circular polarization have 0.3%.

The Swift observation was performed on Feb. 26, 2007, between 20:31–22:37 UT, in response to a 1.5 mag optical brightening the day earlier. We attempted quasi-simultaneous SMARTS observations, which in the end happened 79 min before the X-ray observation. V504 Cen is not detected at X-rays, but clearly in the UV filters. Applying an extinction correction of  $A_V=0.59$  mag, the UVOT and SMARTS data nicely follow the Wien-tail of a blackbody spectrum. The X-ray upper limit constrains the temperature of any hot component in the system to  $kT < 20$  eV (Fig. 4).



**Fig. 4** Spectral energy distribution of V504 Cen from quasi-simultaneous observations of Swift and SMARTS on Feb 26, 2007. No X-rays are detected (upper limit shown as arrow), and the Swift/UV and SMARTS data are consistent with a 35 000 K (3 eV) accretion disk, hotter than the canonical 10 000 K.

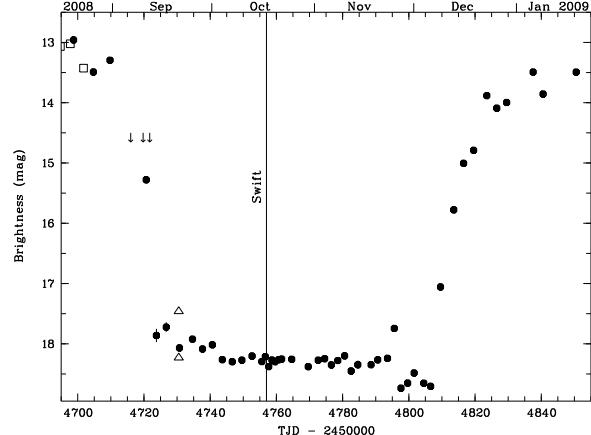
## 2.2 VY Scl

The prototype of the class, VY Scl, started to transition into an optical low state in early September 2008. Our SMARTS coverage is reasonable, and shows that the transition happened within less than 12 days (Fig. 5). There is a further drop in intensity after another 15 days. The  $\sim$ 10 day period of even lower intensity just before the (slow) rise into the high state is also remarkable. This was the first deep low-state of VY Scl since 1983 (Cropper and Warner 1983), after a shallow one ( $B \sim 15.5$  mag) reported via VSNET in Dec. 2003. The low-state ended after only 3 months.

A 10 ksec Swift ToO observation was obtained a week after reaching the  $B \approx 18.2$  mag base-level. Only 37 photons are detected, which are spread in energy up to 6 keV. The observed 0.5–10 keV X-ray flux is  $1.2 \times 10^{-12}$  erg cm $^{-2}$  s $^{-1}$ , corresponding to a luminosity of  $3.5 \times 10^{31}$  (D/500 pc) $^2$  erg/s. This is slightly smaller than the upper limit obtained from ROSAT observations in 1990 (Greiner 1998).

## 3 Summary

For V504 Cen, we tested for a hot source in March 2006. The optical spectra do not show any significant sign of HeII emission, and Chandra and XMM ToO observations do not show a strong supersoft X-ray component. The magnetic option was tested with spectro-polarimetry, but no sign of a substantial magnetic field was found. It thus appears that the suspected H surface burning during the low-states in VY Scl stars either happens at very low temperatures (below 20 eV), or is not a generic feature in this class of objects. Similarly, a magnetic nature of the WD could not be proven. This indicates that in V504 Cen both scenarios proposed as “unconventional” views could not be substantiated, but also the conventional Lagrange point blockage model is challenged by the very long duration of the optical low-state.



**Fig. 5** B band light curve of VY Scl (filled symbols) as obtained with our SMARTS program. Open squares and upper limits (arrows) are from ASAS (reported via VSNET), while the two open triangles are V-band CCD observations (J. Temprano & Cantabria Obs.).

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